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# A Preliminary Low-Frequency Electromagnetic Analysis of a Flux Concentrator

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The objective of this investigation was to conduct a quick, preliminary transient magnetostatic analysis of a Brechna-type[1] flux concentrator to determine its feasibility for collecting positrons in the International Linear Collider. The magnetostatic transient module of Maxwell 3D, Version 10, from the Ansoft Corproartion was used to model the flux concentrator. The solid model is shown in Figure 1.

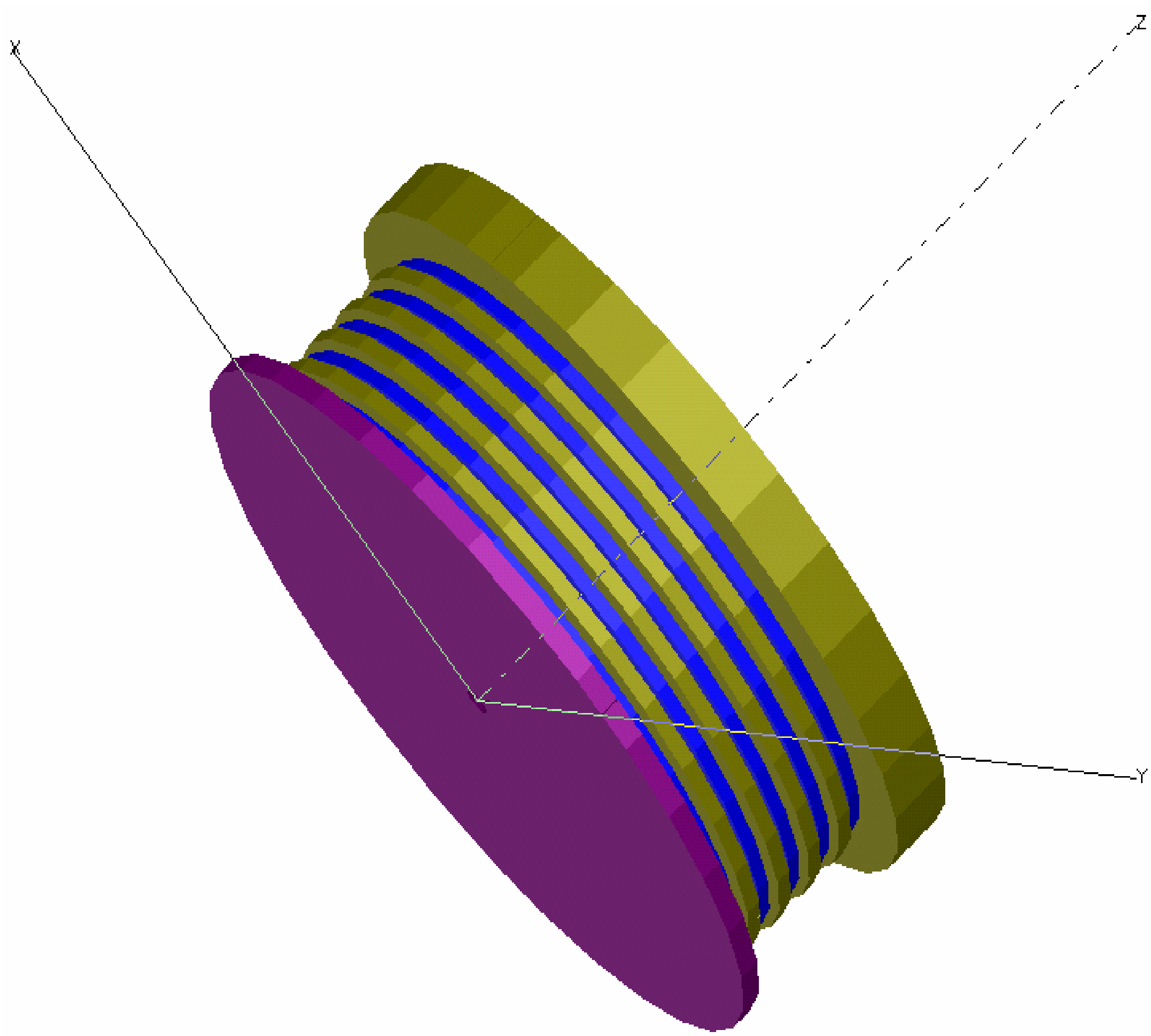


**Figure 1 The solid model of the flux concentrator.**

The flux concentrator, based on the design of Brechna, Hill, and Bailey[1], consists of six circular copper plates and five copper coils. The entire assembly is 19.33 cm in length. The entrance plate, Plate 1, is shown in purple. It has an axially contoured entrance hole in the center, an outer diameter of 53.34 cm, and a thickness of 1.5 cm. The entrance plate is followed by five plates, shown in green. Each of these five plates has a cut out region into which a pancake electrical coil, shown in blue, fits. Each coil has an inner diameter of 20.6 cm, an outer diameter of 46.6 cm, and a thickness of 0.95 cm. Each coil consists of two axial layers, wound from rectangular oxygen free hard copper (OFHC) wire of 0.475 cm in axial extent by 0.381 cm in radial extent. Each layer is assumed to consist of 26 turns. Each coil is modeled as a solid, annular disk. The details of the turn-to-turn and layer-to-layer insulation are ignored. The coils are further assumed to be connected in series to a voltage source, which produces a train of identical square pulses. In this model, the five coils float in vacuum without physical contact with the plates. A quarter section of the solid model is shown in Figure 2.

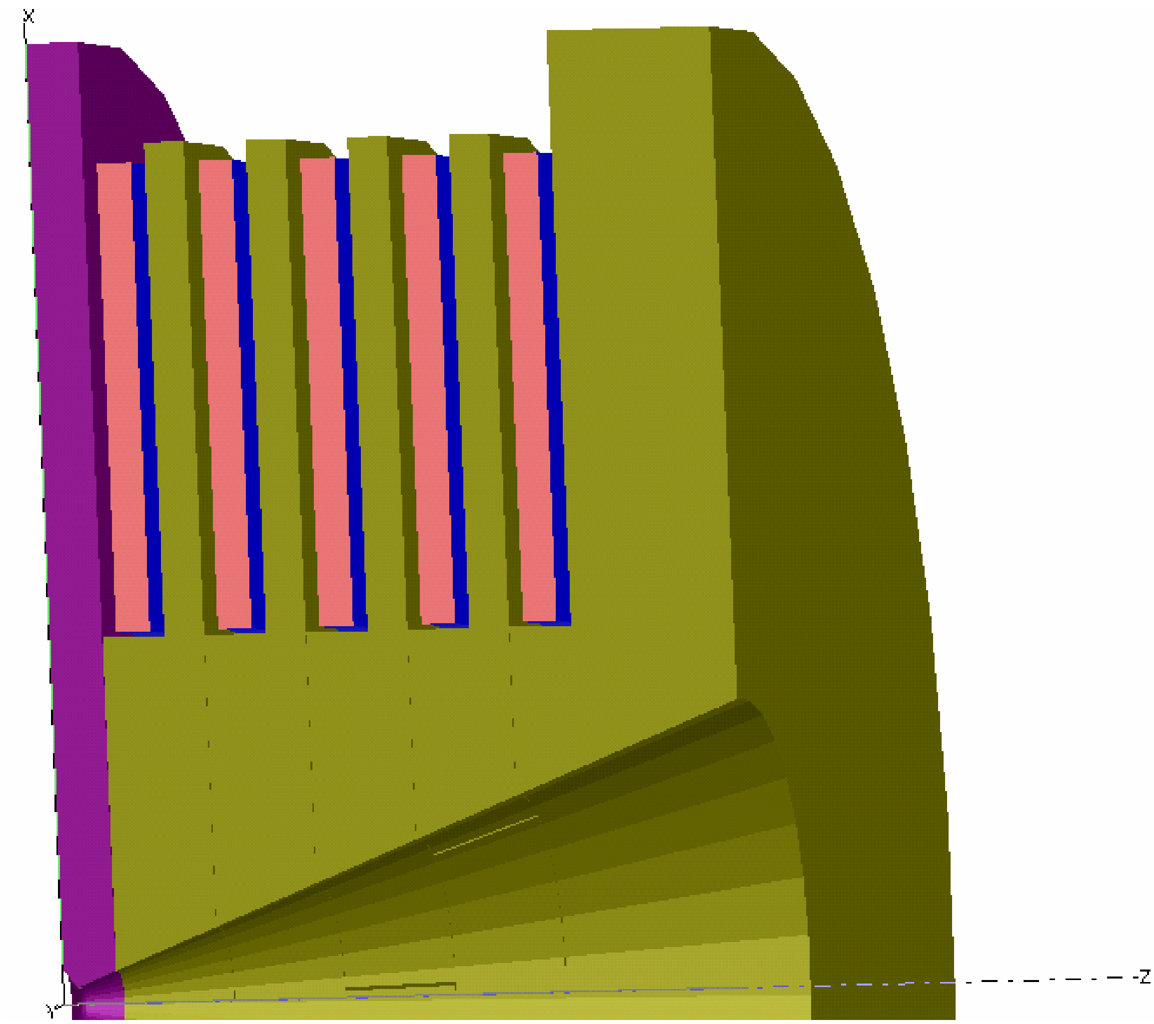


**Figure 2 A quarter section of the solid model.**

In the model, each plate is separated from the other plates by 0.01 cm of vacuum for electrical insulation. These spaces show up as dashed lines between the plates in figure 2. The plates are numbered from the entrance at the origin of the coordinate system. Except for the central vacuum cone, Plates 2 through 5 are identical. Each coil space is 20.3 cm in diameter by 1.74 cm in thickness. Each coil separator is 47.7 cm in outer diameter by 1.12 cm in thickness. For the end plate, Plate 6, the coil space is the same as those of the previous plates, but the end of the plate is 53.34 cm in outer diameter. Plate 6 has a total thickness of 6.34 cm. The vacuum cone cut into the plates begins at 0.5 cm into Plate1 with a diameter of 1 cm and ends at the right side of Plate 6 with a diameter of 8 cm. The cone half angle is 21.72 degrees. That for the Brechna[1] design is 30 degrees. The rectangular features seen on the inner bores of Plates 4 and 5 are the ends of insulating slits in the plates, which are cut into each of the plates. The slit in Plate 1 is 2 mm thick. The slits in the other plates are 1 mm in thickness. The slit in Plate 1 is centered on the yz plane. It was necessary to make the slit in the first plate larger to generate the computational mesh. The slit in each successive plate is rotated by 60 degrees relative to the slit in the preceding plate. The detail of the central hole in the entrance plate is shown in Figure 3. The hole is 2 cm in diameter at $z = 0$. It is 1 cm in diameter at $z = 0.5$ cm. There is no other significance for the approximate curve chosen, except that it is relatively smooth.

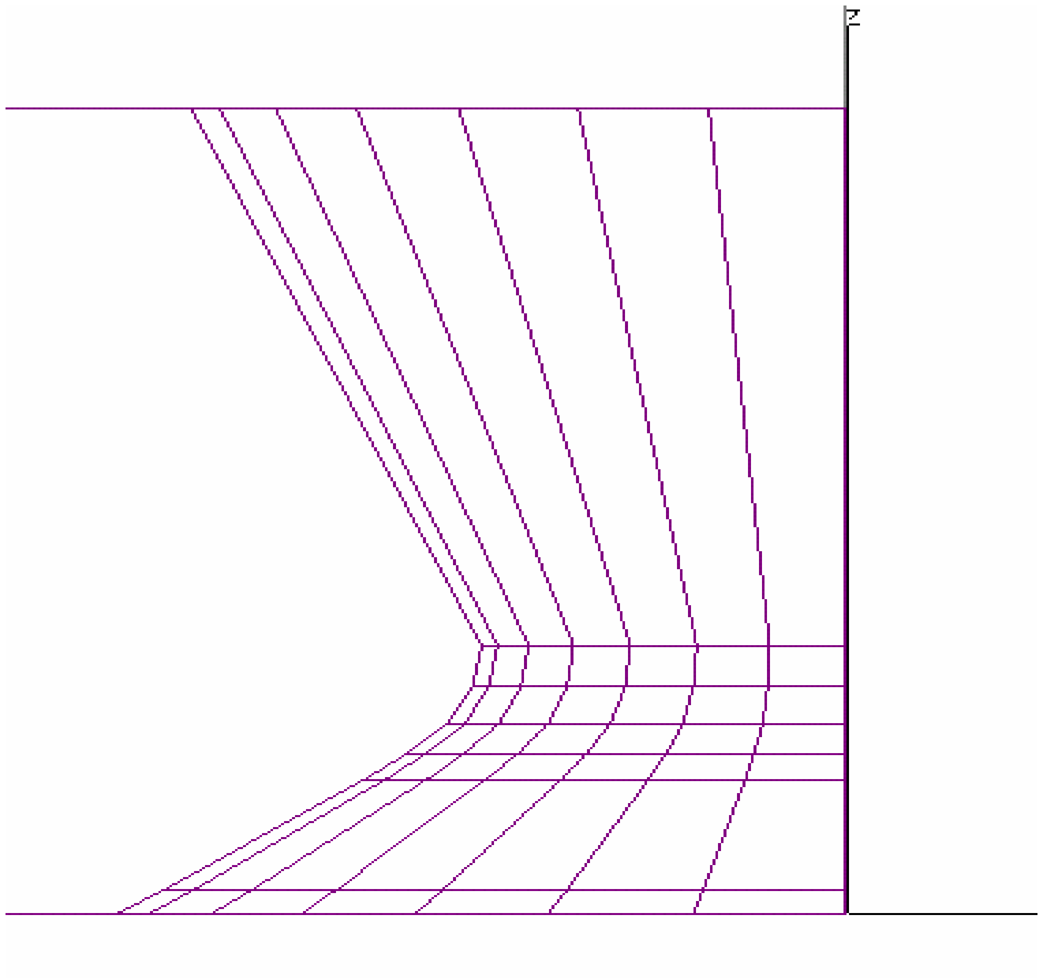

**Figure 3 Details of the entrance hole in wire frame.**

The plates are also assumed to be OFHC. The coils and the plates are assumed to have the resistivity value given by Brechna, Hill, and Bailey[1] in Table I, $2.18\text{x}10^{-7}$ Ohm-cm at 78 degrees K. The series resistance of the coils at 78 degrees K is taken as $3.305\text{x}10^{-2}$ Ohm for the assumed 0.475 x 0.381 cm cross section of each turn.

The voltage produced by the modulator is specified to be a train of perfect square pulses of width 1.2 msec, which occur at 5 Hz. The first of these pulses is shown in Figure 4. As the figure shows, the one time step turn off of the voltage pulse causes the pulse to last somewhat longer than 1.2 msec. The first three voltage pulses are shown in Figure 5.

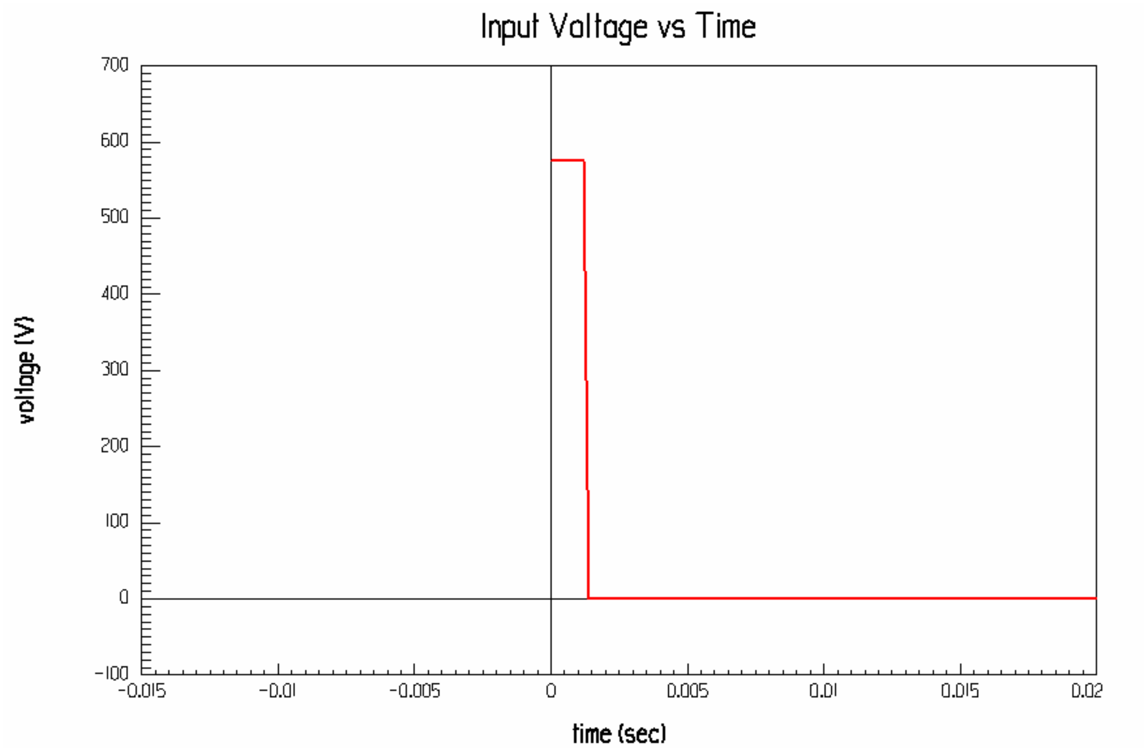


**Figure 4 The first voltage pulse used in the code.**

The computational mesh is fairly compact at 26,877 tetrahedra. The time step is $2 \times 10^{-4}$ sec.

The first pulse of the resulting series current flowing in the coils is shown in Figure 6. We see that this current pulse is a classic L/R response. The current rises in 1.2 msec and then falls exponentially after the turn off of the voltage. The first three current pulses are shown in Figure 7. This figure shows that the reproducibility of the current pulses is good, and each pulse dies out well before the next pulse starts. The first power dissipation pulse in the coils is shown in Figure 8. This is the total power dissipated in the coils for a constant resistance. In actuality, the resistance will increase as the coils heat up. Thus the current will decrease with the heating of the coil. Figures 6, 7, and 8 give worst-case estimates for the peak current and power dissipation in the coils. The peak power is about 1.18 Mw. The average power is about 10.1 kW. The energy in the power pulse is 2.02 kJ. In Table II, Brechna, Hill, and Bailey[1] give 1.6 MW for the peak power input to their magnet, an average power input of 24 kW, and an energy input of 73 kJ per pulse.

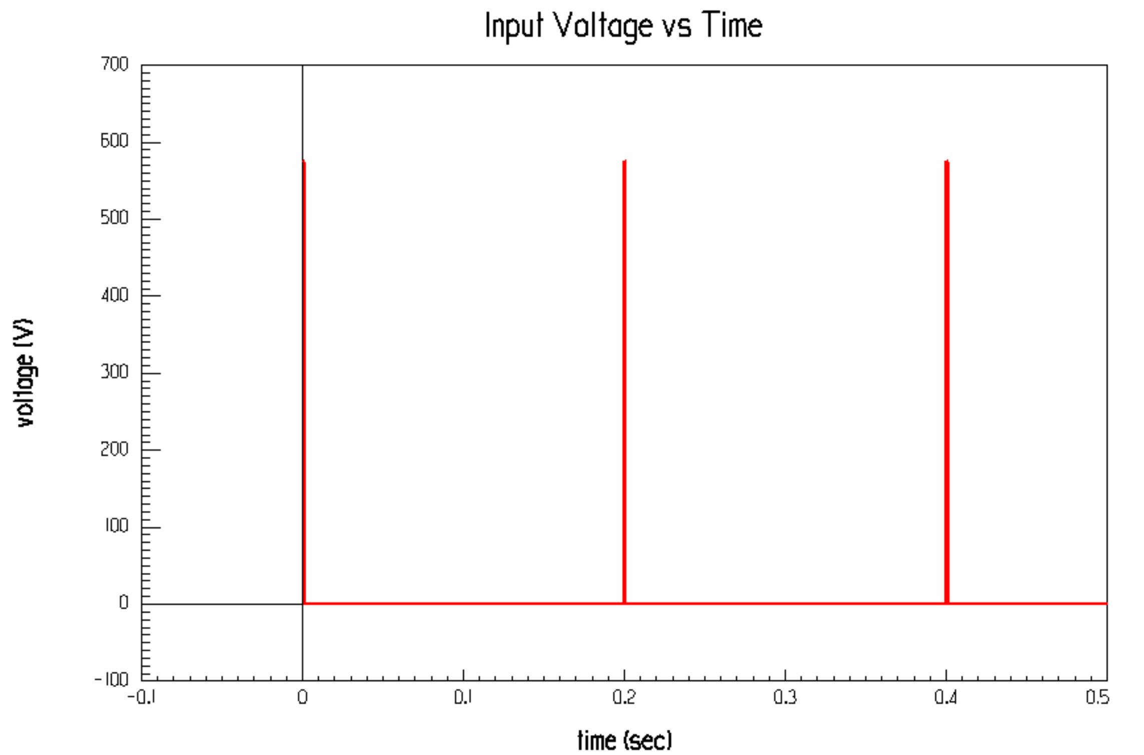


**Figure 5 The first three voltage pulses.**

The eddy-current power loss in the six copper plates is shown in Figure 9 for the first voltage pulse. The peak power loss is about 157 kW. The average power loss is 1.16 kW. The energy in the power loss pulse is 232 J. The code assumes that the resistivity of the copper plates remains constant with time. In actuality, the plates will heat up non-uniformly in time. The effective resistance will be higher than in the calculation. The peak current in the plates will thus be lower than in the calculation. The peak power and dissipated energy will both be lower. Figure 10 shows the first three eddy-current power loss pulses in the plates. We see that the eddy-current power loss pulses for the plates are reproducible. This implies that the eddy currents in the plates due to a voltage pulse die out before the next pulse begins.

The magnitude of the B field on the z-axis, which is the centerline of the flux concentrator, at 0.001 sec is shown in Figure 11. The plot begins at 4 cm in front of the entrance plate of the flux concentrator. At 4 cm on figure 11, the flux concentrator begins. The amplitude of the coil voltage pulse(575 V) has been adjusted to give the 6 T peak value. We see that a B field magnitude of about 1.5-2.25 T occurs from 0 cm to 4 cm in front of the entrance plate. The linearity of the field in front of the flux concentrator entrance is expected to disappear when the computational mesh in this region is refined. The bumpiness of the rest of the field distribution should also disappear with mesh refinement. The peak value of the B field should be somewhat higher at the end of the voltage pulse at 0.0012 sec. It should be possible to tailor, as desired, the axial B field distribution by altering the details of the flux concentrator geometry.

An energy balance calculation can be performed to crudely estimate the temperature rise in the coil per pulse with no cooling from the formula,

$$\Delta T = E/(C\rho V), \qquad (1)$$

where E = 2020 J is the energy deposition, C = 0.205 J/(g-degree K) is the specific heat at 80 degrees K, $\rho$ = 8.933 g/cm$^3$ is the mass density of copper, and V = 5176 cm$^3$ is the estimated total volume of the coils. Substitution of the numerical values into Equation 1 gives 0.213 degrees K per pulse. Cooling will be needed for continuous operation over long periods of time, since operation for 5 min without cooling will increase the temperature by 320 degrees K.

The energy deposition into the six plates is 232 J, and the estimated volume is 23.08 x10$^3$ cm$^3$. A similar simple energy balance for the six plates considered a bulk conductor with uniform heating and no cooling gives a temperature rise of 5.50x10$^{-3}$ degrees K per pulse. Operation for 5 min would raise the plate temperature by 8.25 degrees K. But, this estimate is totally incorrect since the eddy currents flow in thin layers about the perimeter of the slit plates. The highest currents will flow around the inner bores of the plates. The heating of the plates will be locally strong and very non-uniform. The greatest heating should occur in the first plate since it has the smallest bore.

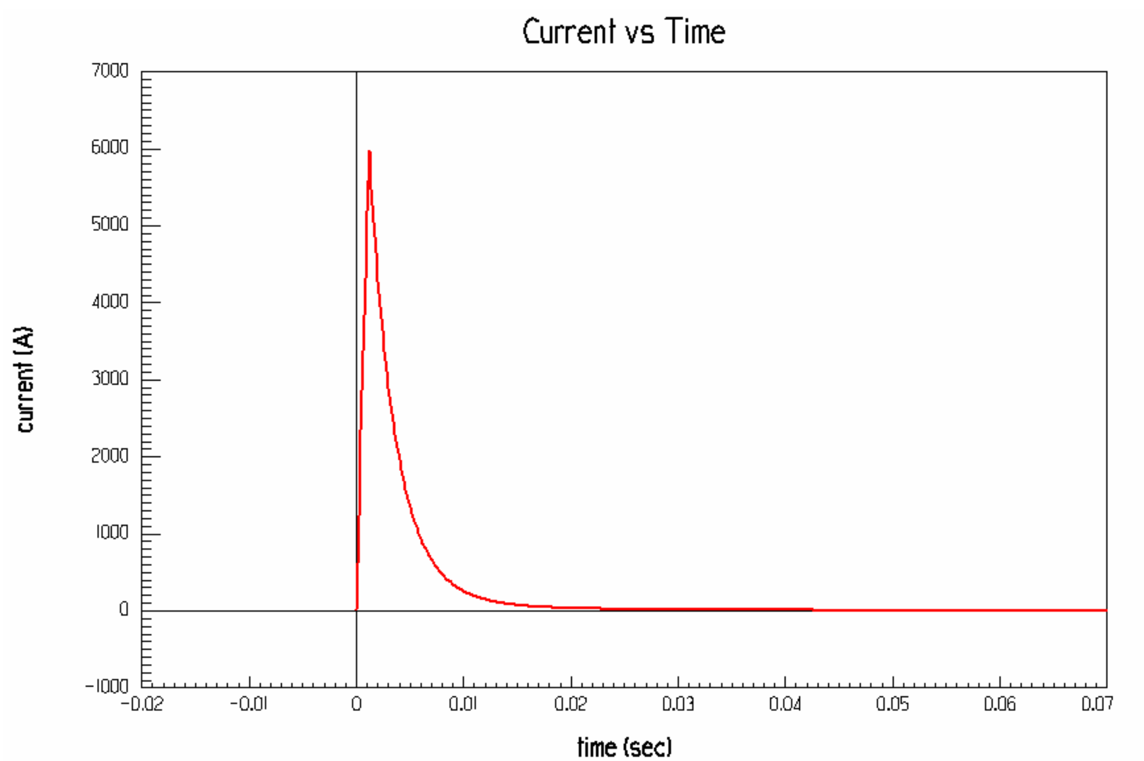


**Figure 6 The first current pulse in the coils.**

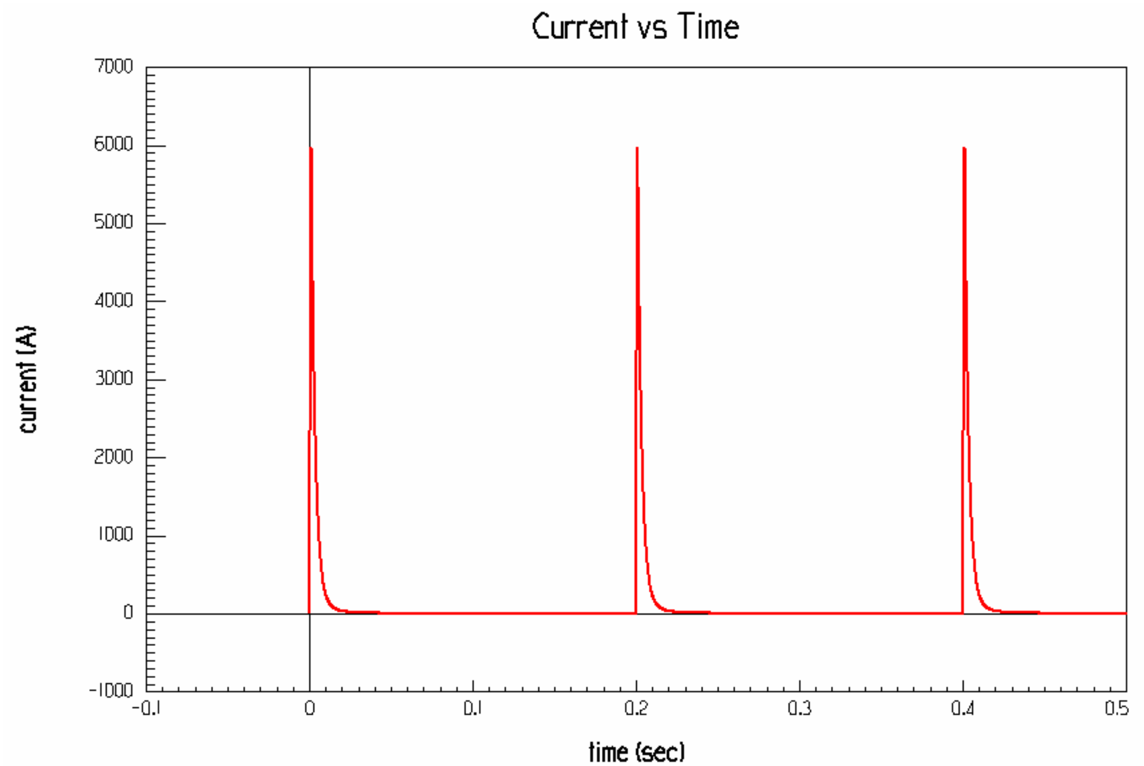


**Figure 7 The first three current pulses.**

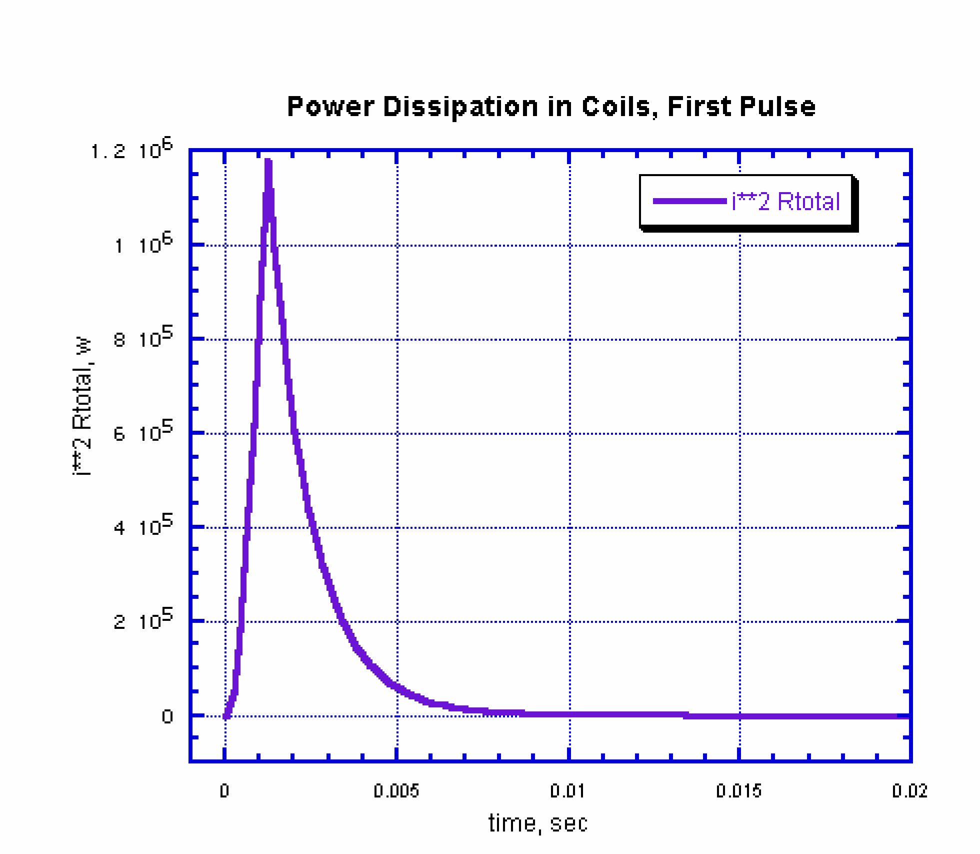


**Figure 8 The first power dissipation pulse in the coils.**

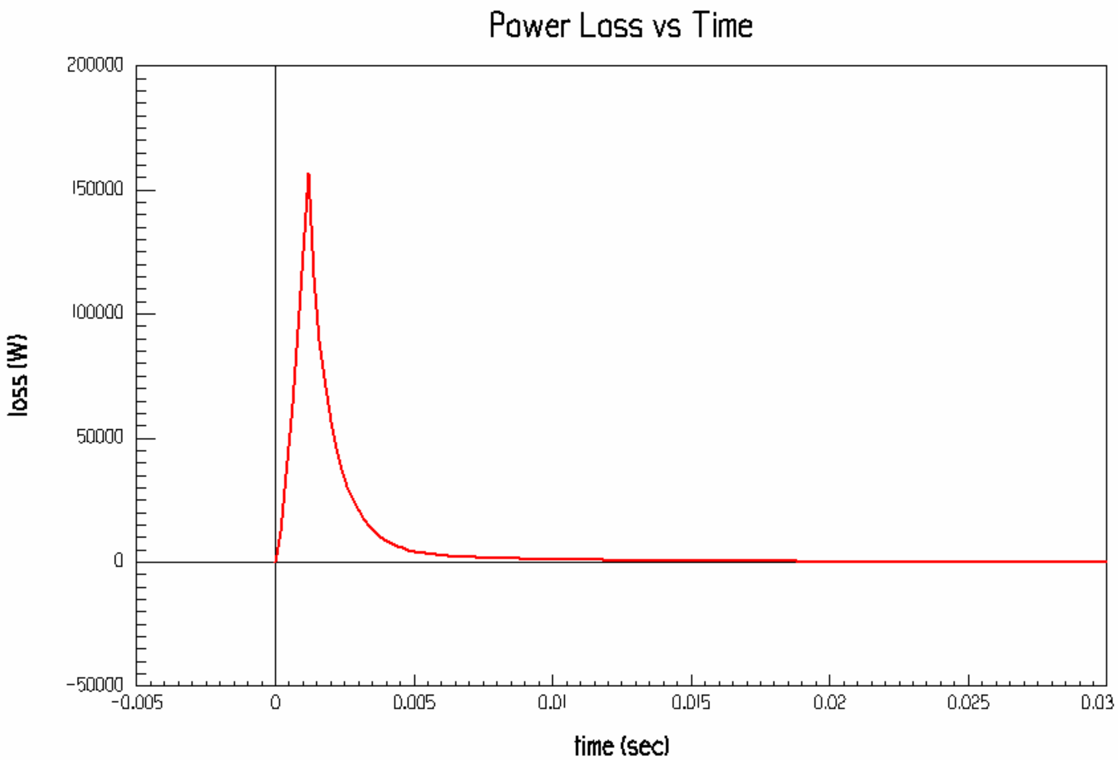


**Figure 9 The first eddy-current power loss pulse.**

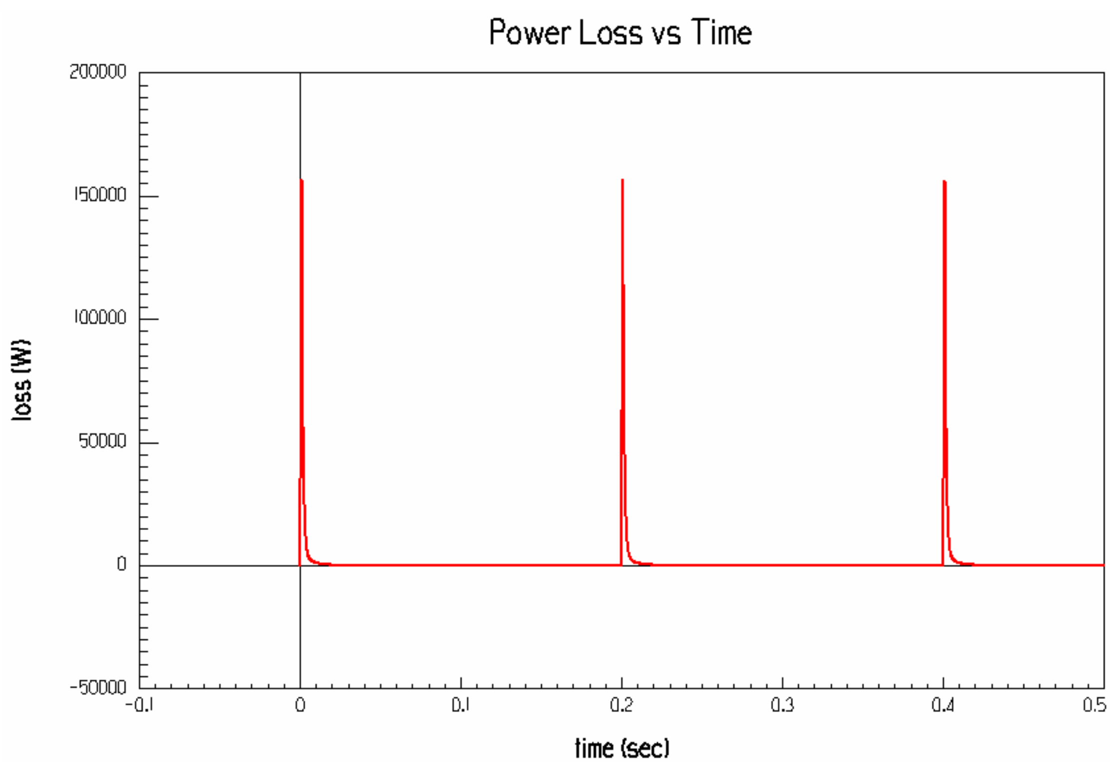


**Figure 10 The first three eddy-current power loss pulses.**

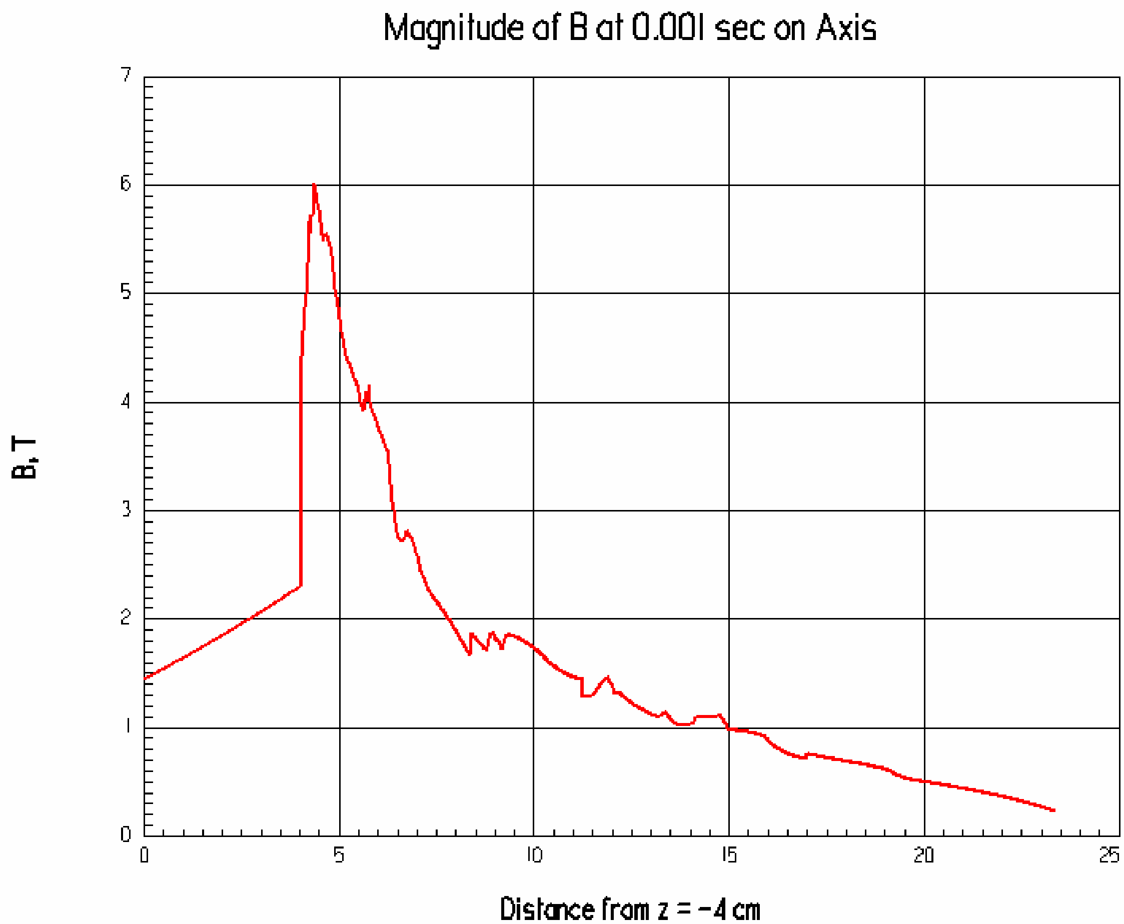


**Figure 11 The magnitude of the B field along the z axis.**

## Conclusions

Preliminary, transient, magnetostatic code calculations show that an axial B field magnitude of the desired level can be produced in the throat of a flux concentrator of the Brechna type. It should be possible to vary the dimensions and the coil parameters to produce desired axial B field profiles. The peak power deposition in the coils and the plates is about 1.34 Mw. The average power deposition in the coils and the plates is about 11.3 kW. The energy deposition per pulse in the coils and the plates is 2.25 kJ. These three values are less than the corresponding values reported by Brechna, Hill, and Bailey[1] for a device with a higher duty cycle, which operated satisfactorily at 3 Hz. Therefore, it should be possible to build a similar device for operation at 5 Hz and a duty cycle of one 1.2-msec-long square voltage pulse five times per second. If the voltage pulses are sufficiently longer than 1.2 msec, operation may still be possible, but cooling will be much more challenging. The voltage modulator duty cycle is very important for minimization of coil and plate power losses.

## Further Work

More detailed analysis of the time-dependent eddy-current power dissipation in each of the plates is required. A prescription for generating the code for doing this has been obtained, but has not yet been implemented. A further refinement will be to obtain the power deposition in radial and possibly azimuthal zones of each plate. It should then be possible to do detailed heat transfer calculations for various cooling tube designs.

Material stress calculations also need to be done to make sure yield levels are not exceeded. Both JXB or Lorentz and thermal stresses will occur and must be considered.

**References**

1. H. Brechna, D. A. Hill, and B. M. Bailey, “150 kOe Liquid Nitrogen Cooled Pulsed Flux-Concentrator Magnet,” The Review of Scientific Instruments, V. 36, No. 11, Nov. 1965, pp.1529-1535.